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*SWAC*

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# National Bureau of Standards Western Automatic Computer

## *recent developments and operating experience*

SWAC—the National Bureau of Standards Western Automatic Computer—is now being operated 24 hours a day, 5 days a week to solve a wide range of complex problems in physics, engineering, mathematics, statistics, and meteorology. At present over 70 percent of this time is devoted to problem solution, the remainder being reserved for maintenance, engineering development, and testing of new equipment.

SWAC is a general-purpose digital computer constructed by NBS in 1950 under the sponsorship of the Wright Air Development Center. The first of the high-speed electronic computers to be completed with the very fast Williams-tube (cathode-ray tube) memory, SWAC operates at a rate of 16,000 additions or 2,600 multiplications per second.

Recently the scope and complexity of the problems that the machine can handle have been greatly extended through the installation and successful operation of a magnetic-drum auxiliary memory. Based on the principle of the magnetic-tape recorder, the new memory holds 16 times as much mathematical information as the cathode-ray-tube memory, with which it will be used to increase the overall memory capacity of the machine. The magnetic drum will also act as a storehouse for a library of numerical methods or routines of instructions which, when obeyed by the machine, can facilitate the solution of a large class of problems.

SWAC was designed and built at the NBS Institute for Numerical Analysis in Los Angeles to provide a rapid, powerful computational tool on the West Coast and to aid in the Institute's program for the further development and increased utilization of the art of machine computation. The ultra-high-speed machine has been used by NBS principally to solve aircraft problems originating with the Air Force and its contractors, other problems in science and engineering submitted by Government agencies, and mathematical problems arising in connection with the Bureau's work on computation methods and computing machine development.

SWAC's high-speed results from its special Williams-tube memory and its parallel mode of operation. The memory unit consists of a bank of cathode-ray tubes that store information as bright spots of charge. The unit is operated in parallel, that is, all the digits of a number are transferred in or out of the memory simultaneously, thus greatly reducing the time required for transfer of information. In serial machines, such as



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those using acoustic-delay-line memories, numbers and instructions are represented by trains of electrical pulses. But in SWAC parallel circuits transfer numbers and instructions almost instantly, within the time of a single pulse (about one tenth of a microsecond). Arithmetic operations are also carried out in parallel, with a consequent increase in speed of computation. In its parallel method of operation SWAC differs from SEAC (National Bureau of Standards Eastern Automatic Computer), a serial machine constructed by NBS at its Washington (D. C.) laboratories

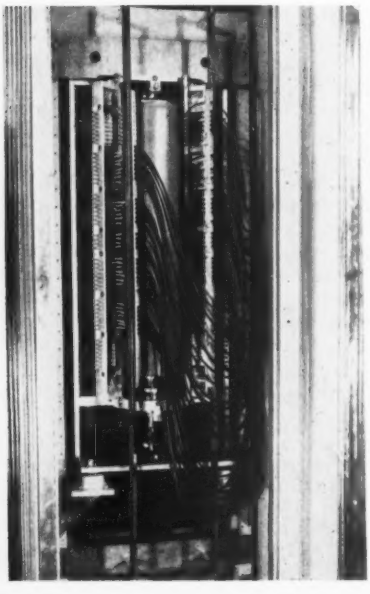
### Magnetic-Drum Memory

While the cathode-ray-tube type of memory delivers information at a very rapid rate, its capacity is limited by the number of digits that can be stored on the face of a single cathode-ray tube. To provide greater flexibility and computing power, a magnetic drum external memory was developed by R. Thorensen and associates of the NBS staff. With the drum memory, many complicated types of problems can be handled by transmitting information out of the computer for storage and then feeding the information back into the computer at a later stage of the problem.

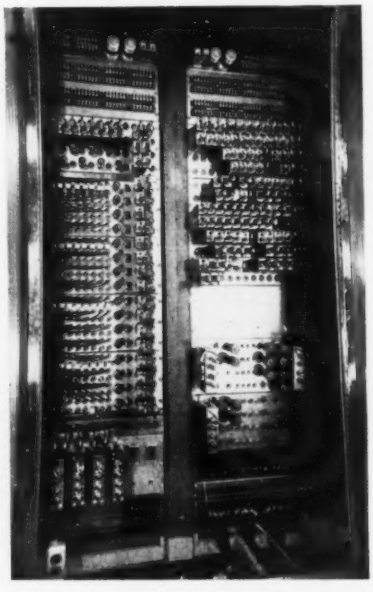
SWAC's drum memory, like those developed elsewhere, is a revolving metal drum that retains numbers and instructions on its surface in the form of magnetic pulses like those used in tape recording. At intervals, blocks of magnetic pulses are removed from the drum by a magnetic head and are taken into the computer to be transformed electronically into spots of charge in the Williams-tube memory, where they remain until called for by the control unit.

SWAC stores and processes information in units called words, each word consisting of 37 binary digits, the equivalent of 11 decimal digits. (The binary number system is analogous to the decimal system, but its base is 2 rather than 10.) The magnetic drum has a capacity of 4,096 words of 37 binary digits each, in contrast with the 256-word capacity of the cathode-ray–tube memory. This high-capacity memory makes possible the solution of very large sets of simultaneous equations, such as arise in logistics; certain types of partial differential equations that occur frequently in aeronautical research, in heat-transfer problems, in electromagnetic theory, and in other fields; and combinatorial problems, applications of which have recently engaged the attention of scientists. Instruction routines stored on the drum will handle, among other things, the conversion of information from a decimal representation into the binary representation used by the machine, as well as the final conversion back to decimal form when it is required to print out results.

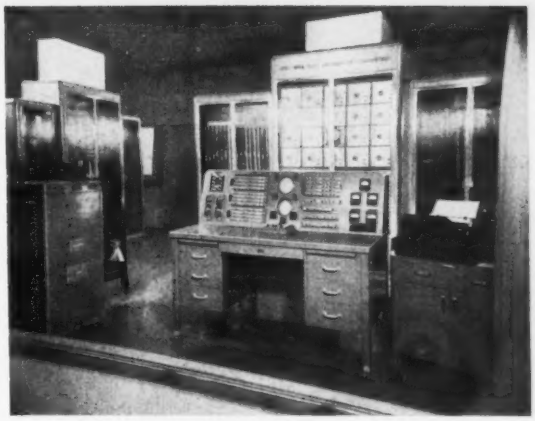
In the construction of the magnetic drum, primary consideration was given to simplicity of design and maximal efficiency in the transfer of information between it and the cathode-ray-tube memory. A drum memory ordinarily has a much larger capacity than a Williams-tube memory, but access to a drum memory is generally slow. In particular, if information is required from some specific location on the drum, the computer may have to wait up to a maximum of one drum revolution before receiving any information. However, in the magnetic-drum memory developed for SWAC, access time is shortened in two ways: (1) Numbers are transferred in sizable blocks from the magnetic drum memory to the cathode-ray tube memory, thus



**Magnetic drum auxiliary memory recently added to SWAC to increase its problem solving capacity. The revolving metal drum retains numbers and instructions on its surface as magnetic pulses. Blocks of magnetic pulses are removed from the drum by a magnetic head and taken into the computer to be transformed electronically into spots of charge in the Williams tube memory.**



**Control circuitry for this memory. The high storage capacity of the drum memory makes possible the solution of very large sets of simultaneous equations, such as arise in logistics; certain types of partial differential equations which occur frequently in aeronautical research, heat transfer problems, electromagnetic theory, etc.; and combinatorial problems.**



**General view of SWAC, showing Williams memory behind operating console (center foreground), cabinets containing control unit on either side of memory, other cabinets in left background containing magnetic-drum auxiliary memory and its control circuitry, punched-card input-output system in front of magnetic-drum memory, and paper-tape input unit on right of console.**

minimizing the total number of times the drum memory must be consulted. (2) The numbers in each of these blocks are stored sequentially around the cirmumference of the drum so that one block forms a band or channel completely encircling the drum. When a transfer to or from the drum memory is made, the whole channel is handled at one time. Transfer of information starts immediately after the proper channel has been selected and continues for exactly one drum revolution, thus eliminating all waiting time. In this way the access time per word is reduced to 500 microseconds—about $\frac{1}{30}$ of the normal access time of a magnetic drum memory.

Information is stored serially on the drum in 40-binary digit words. The first 36 digits represent numerical information, the 37th digit gives the algebraic sign, while the remaining three digit positions are empty. Thirty-two words are stored in each channel and constitute a basic transfer block. As the drum rotates at 3,600 revolutions per minute, 32 words are transferred in approximately 17 thousandths of a second.

The drum contains 128 information channels plus 4 timing channels. The timing channels feed a timing generator, which generates a pulse for each digit space, a pulse for each word space, and a reference pulse for each revolution of the drum. The pulses marking each word space go to an address counter, which counts from 0 through 31. This counter continuously keeps track of the word spaces as they pass under the magnetic read-write heads. The reference pulse is used to initially synchronize this counter with the drum.

The cathode-ray–tube memory operates in parallel with the serial magnetic-drum memory, and the two are not in synchronism. Direct communication between the memories is therefore not possible. Information from the drum must first be played back into a vacuum-tube shifting register and then transferred in parallel to the cathode-ray–tube memory. Each digit takes 13 microseconds to play back, so the 3 empty digit spaces in each word give a total delay of 39 microseconds between words. This delay is more than adequate for transferring a number from the register to the cathode-ray–tube memory and for clearing the register to receive new information.

The entire drum-memory system consists of less than a dozen different types of basic single-tube plug-in units that are developed to a high degree of stability under the variety of conditions of loading and aging. Only about 250 vacuum tubes are used.

In addition to the drum memory, plans call for a slow-speed auxiliary memory consisting of a magnetic-tape unit. It will have a much larger capacity than the other two memories, holding approximately 4,000,000 binary digits, but its average access time will be quite long—about 3½ minutes.

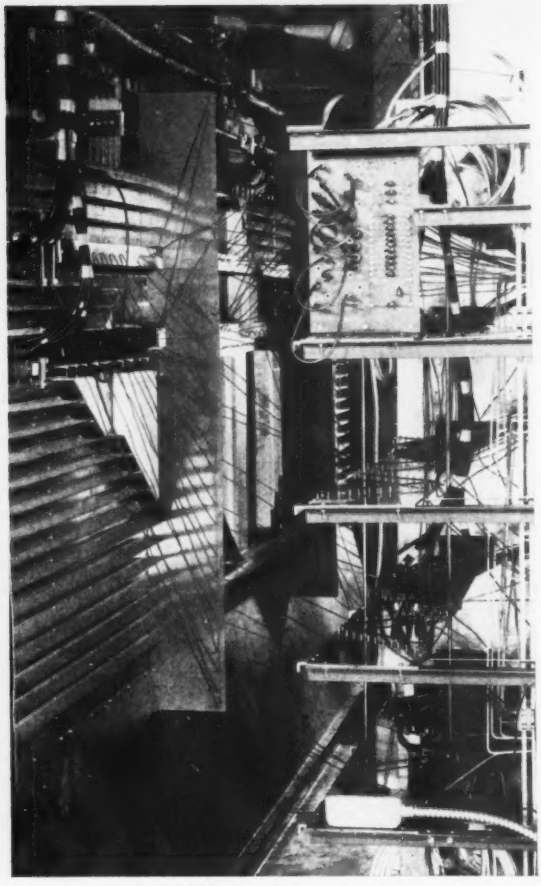
## Description of SWAC

SWAC is automatically sequenced, that is, it automatically performs all of the logical and arithmetical operations required to solve a particular problem once it is supplied with coded instructions and numerical data. The computer stores in its high-speed memory not only the numbers involved in the computation but also the instructions necessary to perform the computation. This makes it possible for the calculator to use fully the speed of the Williams-tube memory, doing complete arithmetic operations in a few microseconds.

The computer proper is housed in a single console approximately 12 ft wide, 5 ft deep, and 8 ft high. It consists of three major parts: An arithmetic unit, a memory unit, and a control unit. Four other parts complete the computer system; they are the magnetic-drum memory, the input-output units, the operating console, and the power supply.

The arithmetic unit performs the arithmetic operations of addition, subtraction, and both rounded-off and exact multiplication. It also performs the logical operations of comparison and extract. Comparison involves changing the course of the computation depending on the relative sizes of two numbers. Extract divides numbers up into parts that the computer can handle in different ways. The arithmetic unit receives information from the memory in the form of numbers to be operated upon and instructions as to the nature of the operation. Having acted upon such instructions and completed the operation, the arithmetic unit returns the answer to the memory.

The memory feeds its information to the arithmetic unit in accordance with instructions it receives from the control unit. The control unit consists of electronic circuits from which control the operations of the computer proper. This unit takes information from the input unit, directs it to the memory, tells the memory when to send information to the arithmetic unit, tells



**Interior view of SWAC. Arithmetic unit is at left, and at right is control circuitry on inner side of console.**

the arithmetic unit when and where to return answers to the memory, and controls the feeding out of completed solutions to the output unit.

SWAC uses both a punch-card input-output system and a paper-tape system. For card input, the coded problem is punched on a standard IBM card, and the answer is received in the same way. In the paper-tape input-output system, a coded problem punched in paper tape is fed into the machine, and answers are automatically given in typed form by an electric typewriter.

The operating console, an office desk with specially built panels mounted on its top surface, permits the human operator to control the operations of the machine and to watch the machine as it operates. The console is provided with control switches and neon lights that indicate what is taking place inside the machine. Oscilloscope screens make it possible for the operator to view the memory pattern of any given unit of the Williams tube memory.

SWAC is supplied with electrical power, carefully regulated in voltage, by means of a motor-generator set and related equipment, largely electronic in nature. The computer is thus isolated from line voltage fluctuations that might affect its operation. About 30 kilowatts are consumed when the machine is operating.

## Williams-Tube Memory

The Williams-tube memory consists of a bank of 37 cathode-ray tubes. each of which can store 256 digits on its face in a matrix pattern of dots and dashes. The dots represent "0" while the dashes represent "1". As SWAC is a binary machine, all decimal numbers and instructions are fed into it in a code which utilizes only the digits 0 and 1.

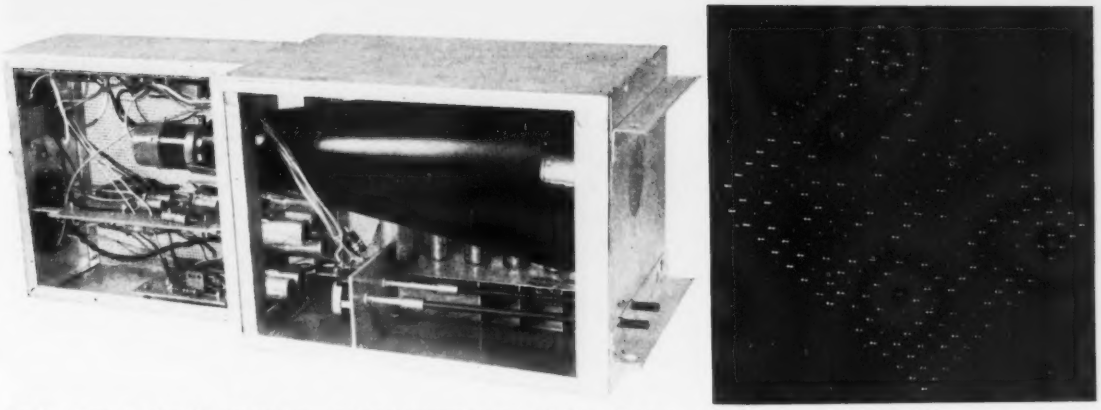
The number of digits that can be stored on the face of one cathode-ray tube determines the number of words that can be stored in the memory. That is, the *n*th cathode-ray tube stores the *n*th digit of each word. Thus, a given word has one digit stored in the same relative position in each of the tubes. This makes it possible to position all of the electron beams at a given location, or address, in the memory and thus to transfer all of the digits of a word simultaneously. As a result, the time required to transfer a word to or from the memory is only 16 microseconds.

To produce either a dot or a dash at a given spot on the face of a Williams-tube unit, the electron beam is turned on to produce a spot of charge on the screen. If the beam is left on only long enough to establish equilibrium and is then turned off, a dot is produced. If the beam is left on longer and is deflected from the dot position by the superposition of a small sawtooth voltage on the positioning voltages, a dash is produced. The dots and dashes are read off by an amplifier, which picks up the signal from the tube screen, amplifies and reshapes it, and causes the electron beam inside the tube to place a signal back on the face of the tube.

Unless this type of storage is continually renewed or regenerated, the original charge pattern tends to disappear over a period of time as the charged spots gradually collect stray electrons. Thus, to provide continuous storage, an electron beam is made to inspect successively each point of charge and to energize electronic circuits that, when necessary, restore the charge to its initial value. The regeneration process takes place during short intervals that alternate with the reading-in or reading-out of information in the memory. In this renewal process the machine spends only 8 microseconds on each point of charge on the face of the tube, and complete regeneration occurs 250 times a second. Such a continuous regeneration process makes it possible to store information indefinitely. A crystal-controlled oscillator regulates both the rate of regeneration of the memory and the operations of the arithmetic unit.

## Operating Experience

SWAC contains about 2,600 tubes and 3,700 crystal diodes. The average tube life is between 8,000 and 10,000 hours. To date, very few tubes have been lost on account of heater failure. The largest percentage



***Left:*** **One of the 37 cathode-ray tubes that make up SWAC's Williams-tube memory.** ***Right:*** **Memory pattern of dots and dashes from the face of one of these tube units.**

of tube failures have resulted from low emission and intermittent shorts.

All electronic components in the computer proper are mounted on removable plug-in chassis, so that faulty operation can usually be corrected by replacing a bad chassis with a good spare. The faulty chassis can then be repaired in the laboratory without loss of computer time. The majority of the plug-in chassis contain an average of 10 tubes each; however, the magnetic-drum circuits are built of much smaller units, usually consisting of a single tube.

One of the difficulties encountered with the cathode-ray–tube type of memory is "spillover," or redistribution of charge, which limits the number of times the spots adjacent to a particular spot may be read before the spot in question must be regenerated. To mitigate this difficulty, circuits have been installed that eliminate most of the drift in the patterns on the face of the tubes. A substantial improvement in operating time has resulted.

Other improvements have been achieved by rebuilding certain parts of the circuitry that have shown a high out-of-order maintenance time. A substantial improvement in operating time occurred when an air-conditioning unit was installed to maintain the incoming air in the ventilation system at a constant temperature. This minimized the temperature cycling of crystal diodes and substantially decreased their failure.

General operating efficiency has also been increased by the addition of a loudspeaker and buffer tube with a plug-in arrangement allowing the operator to "listen" to any of the commands in a problem. For example, an alternate succession of add and subtract commands produces an 8-kilocycle note.

Recently, by the addition of one tube and a few crystals, a converting output command was obtained. This command, effective only with the output typewriter and tape punch, converts fractional binary numbers to octal, decimal, or any other base up to 16.

## Problems Solved

During the 8-month period ending June 1, 1953, SWAC spent an average of 53.2 hours a week in actual computing. The remainder of the operating time was spent in code checking, memory adjustment, maintenance, testing of components, and development of improved facilities. More than 50 problems were handled in the past year, ranging from minutes to hundreds of hours in running time. During this period the punched-card input-output systems was operative, but the magnetic drum had not yet been installed.

Problems in least squares, reduction of data, heat transfers, stress analysis, and a tremendous variety of other physical phenomena can be described by systems of linear equations. However, most of the methods now in common use for solving such equations are variations of the elimination method developed by Gauss. These methods all tend to yield answers of low significance when the matrix of the coefficients is almost unity. Using SWAC for extensive numerical trials, M. R. Hestenes and E. Stiefel of the NBS staff recently developed a new approach, known as the conjugate gradient method, which appears to have broad utility for the solution of problems arising in applied physics and engineering. SWAC has now solved many systems of equations of order 10 to 15. Codes have been prepared for the solution of systems of any order up to 45, but no system of that high order has as yet been solved. However, the characteristic values and their associated vectors have been found to nine significant decimal digits for a 45th order system, as well as for systems of order 10 to 20.

In the field of differential equations, a large amount of computing time has been devoted to the study of associated Legendre functions, $p_n^m(x)$, which are important in mathematical analysis of radiation fields from antennae. The specific problem was the determination of the nonintegral values of the order $(n)$ which, for fixed values of degree $(m)$ and argument

**Checking the operation of a part of SWAC's control circuitry.**

$(x)$, would make the value of the function zero. For each combination of $m$ and $x$, an infinite set of discrete values of $n$ will satisfy the requirements. SWAC found the first 30 values of $n$ corresponding to 1 value of $x$ and 3 values of $m$.

With the aid of SWAC, NBS has carried on research in the application of the so-called "Monte Carlo" method to the solution of complicated differential equations and of previously unsolved statistical problems in nuclear physics. The Monte Carlo method, developed by J. von Neumann of the Institute for Advanced Study at Princeton and S. Ulam of Los Alamos Scientific Laboratory, is a new mathematical technique that solves a physical or mathematical problem by creating an artificial statistical model of the physical or mathematical process involved. It applies the same techniques that are used in analyzing games of chance to the analysis of physical problems where the events are random and are governed by the laws of probability. Large-scale computers such as SWAC provide an excellent means for the solution of problems of this kind because they are able to create conditions that imitate the statistical behavior of the given problem. Thus, the randomness of the event can be taken care of by putting into the extended memory of the machine a set of random numbers which are first tested for their random quality. SWAC has been used to compile large groups of random digits, to explore their statistical behavior, and to investigate their utility for solving partial differential equations by random walk processes. Recently problems concerning nuclear forces have been attacked by means of the Monte Carlo method.

Problems in the evaluation of definite integrals have arisen from studies in probability and statistics. One such problem, the computation of a table of survival probabilities for biological experiments, required the evaluation of 12,500 double integrals with each variable ranging from plus to minus infinity. This table was computed in 177 hours. A second table, for biological experiments in which the exact level of a radiation dose is unknown, required the evaluation of 7,500 single integrals, this time with an infinite lower limit and a finite upper limit.

Many applied problems have dealt with the reduction of large blocks of data. A study of the large-scale circulation patterns in the earth's atmosphere was typical. Some 750,000 pieces of data, each 5 decimal digits in length, were processed to yield about the same number of answers. SWAC spent 325 hours on this problem.

SWAC has also been applied to several combinatorial problems. In some it has exhaustively searched through all possible combinations of the variables. One such problem was that of finding different sets, that is, a set of $n$ numbers such that all $n\ (n-1)$ nonzero differences give distinct remainders when divided by $n^2-n-1$. Another problem, involving permutations, dealt with the optimal assignment of duties in an organization.

SWAC has proved an effective tool for the analysis of Fourier synthesis of X-ray diffraction patterns of crystals. Such analyses, at present being carried on by members of the Chemistry Department of the University of California at Los Angeles, lead to the determination of the arrangement of molecules inside the crystals.

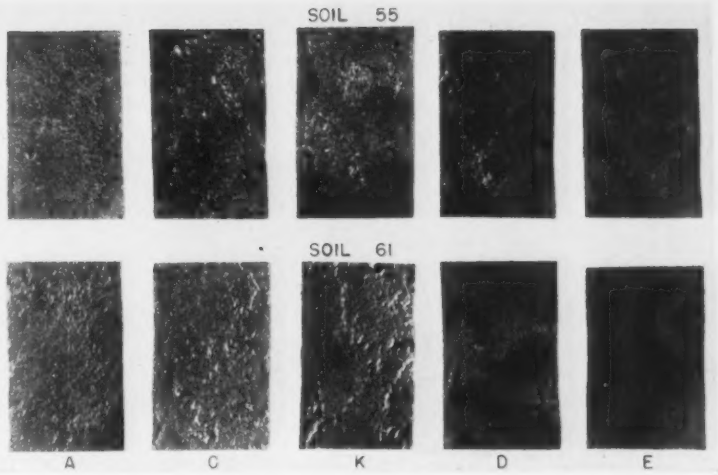
In the field of pure mathematics, SWAC has been used to study the primality of Mersenne numbers, that is, numbers of the form $2^p-1$, where $p$ is a prime. These numbers, when prime, are related to the "perfect numbers" of the Greeks, which are the sum of all their integral divisors excluding themselves. The present list of values of $p$ that yield prime numbers is as follows:

2, 3, 5, 7, 13, 17, 19, 31, 61, 89, 107, 521, 607, 1,279, 2,203, and 2,281.

The last five values were added to the list by SWAC as a result of the systematic testing of all prime numbers up to 2,297.

Mathematical research directed toward more effective utilization of electronic digital computers is continuing at the NBS Institute for Numerical Analysis. Further progress in this program should materially increase the scope of the problems that SWAC and other high-speed computers can handle and should also make possible additional savings in actual computing time.

*For further technical details, see* The SWAC—design features and operating experience, *by H. D. Huskey, R. Thorensen, B. F. Ambrosio, and E. C. Yowell, Proc. IRE (October, 1953). For details about SEAC, see* SEAC, *NBS Technical News Bulletin* **34,** *121 (Sept. 1950).*




**Various low-alloy irons and steels investigated by NBS differed widely in resistance to underground corrosion. These steel specimens buried in two typical soils for 13 years indicate improved corrosion resistance that results from increasing the chromium content. A, plain open-hearth steel; C, steel with 1.02 percent chromium, 0.42 percent copper; K, steel with 2.01 percent chromium, 0.57 percent molybdenum; D, steel with 5.02 percent chromium; E, steel with 4.67 percent chromium, 0.51 percent molybdenum. Soil 55 (upper row) was well-oxidized acid silt loam deficient in soluble salts; soil 61 (lower row), poorly aerated clay containing a moderate amount of soluble material.**

# Corrosion of Low-Alloy Irons and Steels in Soils

THE EXTENSIVE use of low-alloy, high-strength steels in many kinds of above-ground construction is based largely on the fact that these steels corrode more slowly than plain carbon steels under most atmospheric conditions. Unlike steels containing high percentages of alloying metals, low-alloy steels are not inherently resistant to corrosion. Instead, they owe their corrosion resistance to the development of an adherent layer of corrosion products, which reduces further corrosion to a negligible or at least tolerable rate. Since these protective deposits develop normally under conditions of good aeration, the usefulness of low-alloy steels as a class for underground construction would seem to depend on their ability to develop and retain protective deposits under the conditions of deficient aeration that are characteristic of corrosive soils.

A recent study by the Bureau provides new information on the corrosion of certain low-alloy irons and steels in soils. Specimen plates of several of these materials (containing up to about 6 percent of total alloying elements), together with reference specimens of plain steel, were buried at 15 different test sites for periods up to 13 years.

Included in the Bureau's study, which was conducted by I. A. Denison and M. Romanoff of the NBS corrosion laboratory, were specimens of copper-molybdenum open-hearth irons, nickel-copper steels, and chromium steels with and without molybdenum. Sets of specimens were removed at regular intervals over the 13-year period, and after removal of corrosion products the weight losses and depths of the deepest pits were measured.

The steels containing 4 to 6 percent of chromium generally lost only about half as much weight as did plain steel under the same conditions. However, the greater corrosion resistance of the alloy steels as measured by weight loss was not generally accompanied by a corresponding reduction in the maximum depth of pits. The least pitting was observed on specimens that contained molybdenum in addition to chromium.

The change in the rate of pitting with time was found to depend on the composition of the steel. Although the initial rate of pitting was greater for the alloy steels the depths of the deepest pits in the alloy steels were usually less than in the plain steel. This indicates that after the maximum period of exposure the alloying constituents induce the formation of corrosion products that tend to reduce the rate of pitting with time. In an environment unfavorable to the development of protective deposits of corrosion products the alloy steels could be expected to develop deeper pits than plain steel would, because the greater initial rate of pitting of the alloy steels would tend to be maintained. This tendency toward accelerated pitting of alloy steels was actually observed in a few highly reducing soils in which the deposition of a protective scale was impossible because of the solubility of the corrosion products.

Provided their corrosion resistance in a prospective environment is sufficient, low-alloy steels may be of interest for certain applications because of their high strength. The NBS study indicates that alloy steels may in some cases be appropriate choices for certain types of underground construction, such as piling, in which mechanical strength, rather than ability to contain a fluid indefinitely without leakage, is of primary importance. However, whether the superior properties of an alloy steel justify its higher initial cost should be given due consideration.

*For further technical details, see* Corrosion of low-alloy irons and steels in soils, *by Irving A. Denison and Melvin Romanoff, J. Research NBS* **49**, *315 (Nov. 1952); reprinted as NBS Research Paper 2367, available for 10 cents from the Superintendent of Documents, Government Printing Office, Washington 25, D. C.*

*Below:* Flow diagra of h
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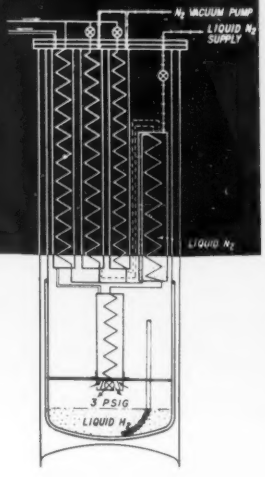



*Left:* Master panel board in hydrogen-liquefaction plant. Identical sections at left are used to control flow of hydrogen through liquefier. Dials record and control level of liquid hydrogen and liquid nitrogen in liquefiers and purifiers, indicate and regulate pressure, and record temperature. End panel section (at right) contains additional temperature recorders and indicators to show amount of gas in external gas holders. Superimposed diagram shows the hydrogen liquefier (exclusive of compression and purification systems).

# NBS-AEC Cryogenic Engineering Laboratory

A MAJOR low-temperature engineering facility, consisting of a liquid-hydrogen plant and a cryogenic laboratory, has been placed in operation at the National Bureau of Standards site at Boulder, Colorado. Known as the NBS-AEC Cryogenic [1] Engineering Laboratory, the new $3,500,000 installation makes possible large-scale production of liquefied gases which have not previously been available in sufficient quantity for laboratory and industrial development and testing.

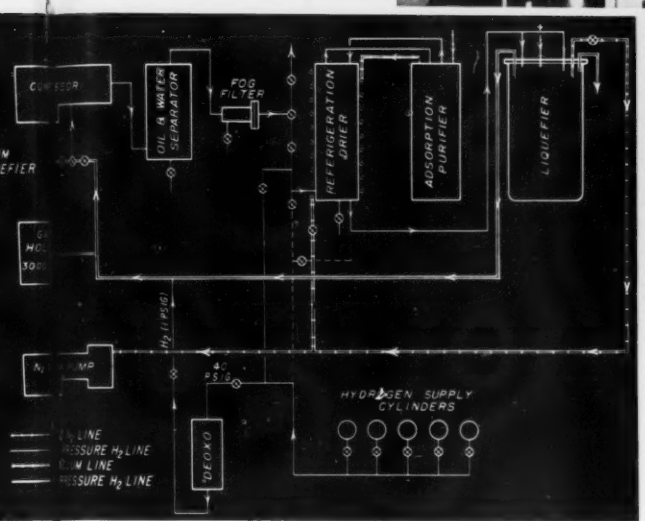
The Cryogenic Engineering Laboratory was initiated by Dr. F. G. Brickwedde, chief of the NBS heat and power laboratories, and was designed under his direction, in cooperation with the Atomic Energy Commission, to provide facilities needed for the development and evaluation of cryogenic equipment for use at temperatures near absolute zero. The Bureau's long-standing program of fundamental research on the properties of liquid helium, superconductivity, second sound, paramagnetism, and other phases of low-temperature physics remains at the NBS Washington laboratories.

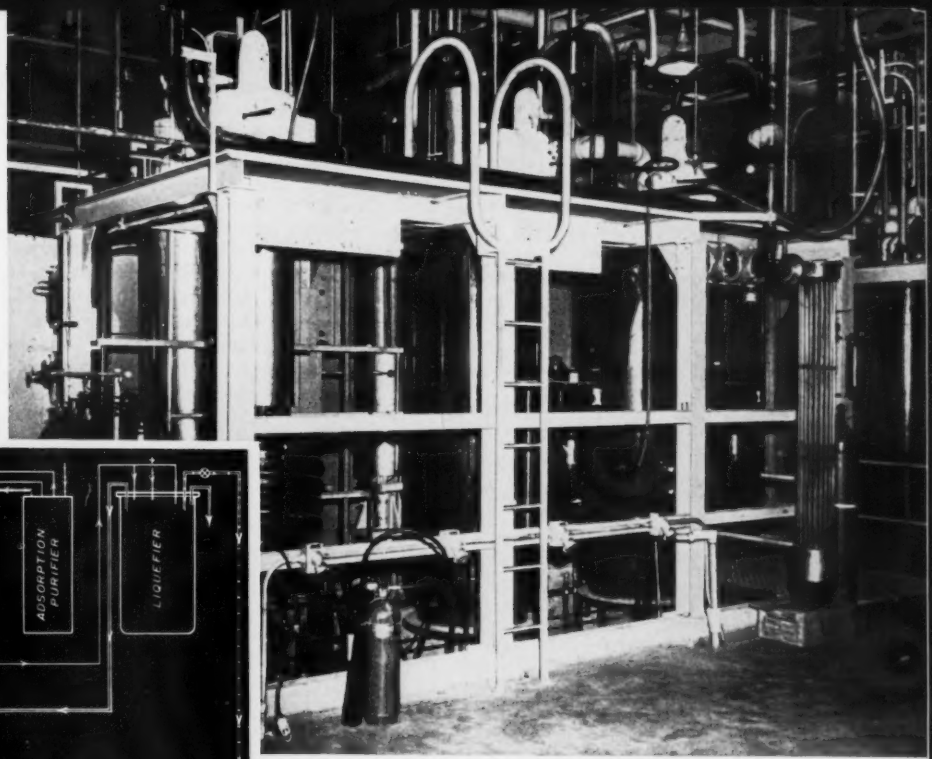
Low-temperature activities at Boulder are carried on by a staff of 60 NBS personnel, under the supervision of R. B. Scott. Besides the production of liquid hydrogen and liquid nitrogen in unusually large quantities, a program of research and development, directed chiefly toward the improvement of low-temperature equipment, is well under way.

Low-temperature liquefied gases—oxygen, hydrogen, and nitrogen—are finding increased application in industry and national defense, making necessary larger, more convenient, and less hazardous equipment for producing and handling these liquids. As a result,

[1] Cryogenic (from the ancient Greek *kryos*, icy cold) is an adjective meaning "very cold" or "at very low temperature."

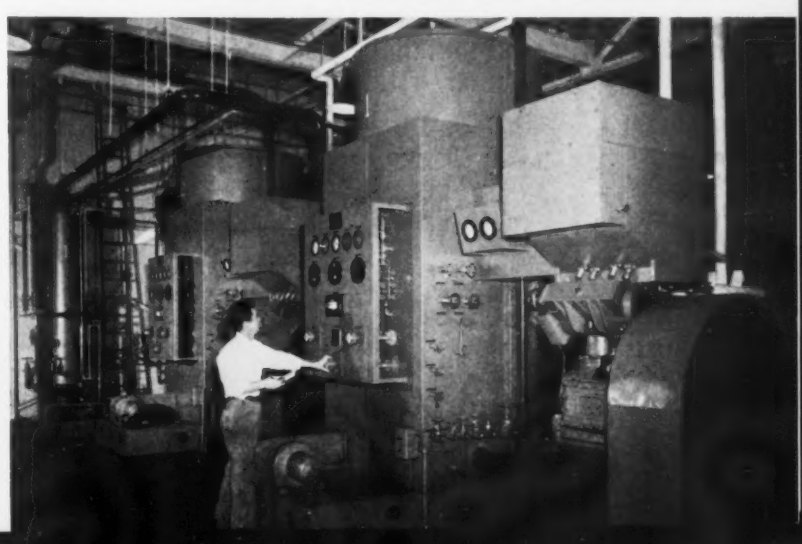
diagra of hydrogen liquefier. *Right:* omple liquefying and purifying systems al passeway) and a portion of second ). M to passageway is 1,000-liter metal ding drogen liquefier. Beside it is second urroding silica-gel purifier. To left of altern or "switch" purifier, from which en moved to expose large coil (below) ca gel d heat exchanger above coil. Tall e behi it and to its left contains refrigera-



many new and highly complex engineering problems have arisen in the low-temperature field, where much remains to be learned about the behavior of engineering materials. At liquid-hydrogen temperatures, normally trustworthy construction steels become brittle, rubbers lose their elasticity, and the mechanical properties of plastics are greatly altered. In general, there are such marked differences between the behavior of matter at ordinary and very low temperatures that the low-temperature properties cannot be obtained by extrapolation. The NBS–AEC Cryogenic Engineering Laboratory is investigating structural and other engineering properties of matter at low temperatures to provide the needed data and is developing more satisfactory materials and equipment for low-temperature use.

The Boulder installation is located on a 210-acre tract, the site also of the Bureau's large radio propagation laboratory now under construction. It consists of three principal units: A liquid hydrogen plant, a liquid nitrogen plant, and a group of laboratories for research and development. Two large concrete buildings—one housing the liquefying plants and the other



**Liquefaction plant contains two liquid-nitrogen generators for nitrogen separation and liquefaction. John E. Schrodt of NBS stands in front of one. Within large cylindrical case is combination liquefier and liquid-air distillation column that removes oxygen from liquid-air mixture. To its right is air-expansion engine. In smaller tank at extreme left is activated alumina for removal of moisture from air.**

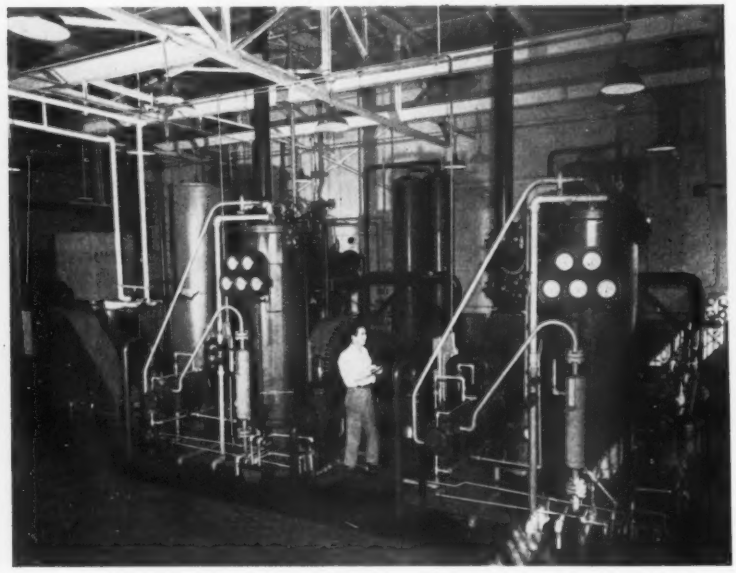
for the experimental laboratories and shop—provide a total floor space of 34,000 square feet. There are also several auxiliary buildings and test sites.

Both major buildings are equipped with many safety and anti-explosion devices to minimize the hazards of working with liquid hydrogen in large quantities. The hydrogen liquefying and purifying equipment, which was designed and constructed by NBS, is in duplicate so that the plant can be operated continuously without shutdown. The experimental laboratories have been designed with emphasis on versatility in order to make possible continuing research in a variety of fields of science and engineering as the need arises.

### Hydrogen Liquefaction

Liquid hydrogen—the lightest of all known liquids—has a density $\frac{1}{14}$ that of water and boils just 20 Centigrade degrees above absolute zero at atmospheric pressure. Only liquid helium has a lower boiling point. Originally classed by Michael Faraday as a "permanent gas," hydrogen has such a low critical temperature (−240° C) that it was not liquefied until 1898. If at ordinary temperatures (above −80° C) hydrogen is allowed to expand through a throttling valve without doing external work—the so-called Joule-Thomson expansion—the result is not a cooling effect, as with most other gases, but a heating effect. Evidently at temperatures above −80° C, known as the inversion temperature, the thermal energy lost by the expanding hydrogen gas (in overcoming the relatively slight forces of molecular attraction between the lightweigh hydrogen molecules) is more than balanced by the heat produced as the expanding gas molecules push each other out of the way. Thus, in order to liquefy hydrogen by expansion, it must first be cooled below −80° C by some other means.

Actually, the further hydrogen is cooled below the inversion temperature before expansion, the greater is the Joule-Thomson cooling effect. For this reason, in the NBS hydrogen liquefier the hydrogen, after first being compressed, is precooled with liquid nitrogen to as low a temperature as possible before the Joule-Thomson expansion. Liquefaction is then accomplished by allowing the compressed, cooled hydrogen to expand through the Joule-Thomson valve from a pressure of about 1,800 lb/in² to atmospheric pressure. For maximum efficiency in cooling during the course of the process, extensive use is made of counterflow "heat exchangers," in which the high-pressure gas is cooled as it passes through many turns of coiled tubing surrounded by colder low-pressure gas moving in the opposite direction from a later stage of the liquefaction cycle.



**Duplicate compressor systems in the nitrogen-liquefaction plant. Air drawn in from the roof of the plant is compressed in five stages to a pressure of 3,000 pounds per square inch. The two large cylindrical tanks in the foreground contain cooling systems for the compressors. The tall cylindrical tanks in the background are caustic purifiers, through which the air is run between the second and third compression stages for removal of carbon dioxide. At the extreme left is the air expansion engine of one of the nitrogen liquefiers, and slightly to the right of the engine is a combination liquefier and fractionation column.**

Commercial hydrogen is transported to the NBS plant for liquefaction in mobile tube banks. The hydrogen is stored in these and in similar stationary tube banks at the Laboratory at a pressure of 2,100 to 2,400 lb/in² until needed in the plant. From the storage tubes, the gas flows at reduced pressure (25 to 50 lb/in²) through a tank containing a palladium catalyst, which removes small amounts of oxygen (by promoting the $O+H_2=H_2O$ reaction), and then to water-cooled four-stage compressors. Two 3,000-cu ft gas holders in the line between the deoxidizing equipment and the compressors provide a ballast for operation of the plant and also serve to maintain a small pressure in the line.

Leaving the compressors at room temperature and a pressure of about 2,000 lb/in², the gas is next purified

by means of a system consisting of oil-water separators to remove suspended liquid, a refrigeration drier to remove water and oil vapor, and an adsorption purifier of silica gel cooled to liquid nitrogen temperature for removal of nitrogen and other gases. After the purified hydrogen has given up some of its heat energy in passing through counterflow heat exchangers, further cooling is attained in the liquid-nitrogen precooler, where the hydrogen passes through coiled tubing immersed in liquid nitrogen boiling at reduced pressure. From the precooler, the gas passes through a final heat exchanger and then through the Joule-Thomson expansion valve, where part of the hydrogen is liquefied by the expansion.

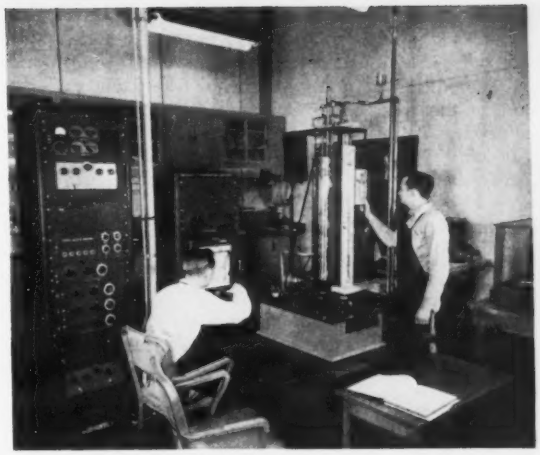
Upon leaving the liquefier, the liquid hydrogen is transferred into storage containers through specially designed vacuum-insulated transfer lines. These "pipelines" have been used to carry the liquid 50 ft or more, and it appears likely that this distance can be greatly extended if desired.

The NBS hydrogen liquefier is unique in that all the heat exchangers as well as the liquid-nitrogen precooler are contained in a single large vacuum-insulated metal dewar having an internal length of 7.5 ft and an internal diameter of 2.5 ft. An identical dewar surrounds the silica-gel adsorption purifier. Inasmuch as the hydrogen liquefying equipment is in duplicate and each liquefier is provided with two silica-gel purifiers for alternate use, the hydrogen plant contains six of the large dewars altogether.

The upper two-thirds of the liquefier dewar contains three heat exchangers and the liquid nitrogen precooler. These heat exchangers are in parallel and are equipped with adjusting valves that permit distribution of the flow of entering hydrogen between the exchangers in such a way as to obtain maximum efficiency in the cooling process. The lower third of the liquefier dewar serves as the liquid hydrogen collection pot. It also contains the final heat exchanger and the Joule-Thomson expansion valve. The portion of the hydrogen that was cooled but not liquefied in passing through the expansion valve is used as a refrigerant in the final heat exchanger and in one of the initial heat exchangers, while the liquid nitrogen vapor from the precooler is the refrigerant in the other two heat exchangers.

The refrigeration drier and silica-gel adsorption purifier are arranged as a unit. Hydrogen gas enters the drier case at room temperature and passes over heat exchanger tubes where it is cooled by outflowing gas inside the tubes. The water and oil impurities are condensed out as the gas flows through the drier toward the nitrogen purifier. The gas is finally cooled to liquid nitrogen temperature by passing through a coil submersed in liquid nitrogen in the purifier dewar. At this temperature nitrogen gas present as an impurity in the hydrogen is readily adsorbed by the silica gel as it flows through the silica-gel coil.

For efficiency and convenience of operation, the hydrogen liquefaction system is extensively equipped with automatic instruments, recording devices, and



***Above:*** **Apparatus for determination of heat-conducting properties of metals and plastics at low temperatures. Heat is applied electrically to cylindrical specimen in cryostat at right. Thermocouple junctions measure resultant temperature gradient. Robert Powell is adjusting smaller potentiometer to measure current and potential of heaters. Paul Baird is using manometer at right of cryostat dewar to read pressure within cryostat.**
***Below:*** **Equipment for study of mechanical properties of metals at very low temperatures. Specimen in cryostat behind panel board is subjected to tensile stress by hydraulic system. Stress, strain, and temperature measurements are being obtained from instruments on panel board by Robert Goettlemen and recorded by Max Crum.**

servomechanisms. For example, level indicators [2] and controllers developed by NBS measure the liquid-hydrogen level and automatically maintain the proper level of liquid nitrogen in the adsorption purifier dewar and in the precooler. An automatic control instrument regulates throttle valves in the vacuum pumping lines to keep the pressure over the pots of boiling liquid nitrogen just above the triple point for maximum cooling without freezing the nitrogen. Another automatic instrument controls the level of hydrogen within the gas holders; thus insuring that new hydrogen gas flows into the system at the same rate as liquid hydrogen is taken out. The nitrogen content of the hydrogen is measured by a thermal-conductivity apparatus, developed in the Chemistry Division of NBS. Finally, whenever a part of the liquefaction plant is not operating properly, a general annunciation system rings a bell and flashes a light that indicates the particular part of the equipment that must be investigated.

### Nitrogen Liquefaction

Liquid nitrogen (99.7 percent pure) for precooling the high-pressure hydrogen in the liquefier is produced in the liquid nitrogen plant, which consists of two complete and independent commercial units for purifying and liquefying the gas. Both units are usually operated simultaneously. Two 11,000-liter insulated storage containers, each having a loss rate of about 1.5 percent a day, make it possible to maintain a large supply of liquid nitrogen at all times.

At atmospheric pressure nitrogen must be cooled to $-196°$ C for liquefaction. In the NBS plant liquefaction is attained a few degrees above this temperature because the pressure of the gas is kept somewhat higher. During the course of the process, nitrogen is separated from ordinary air drawn in from the roof of the plant and is ultimately cooled to liquefaction by a combination of processes involving refrigeration by contact with colder gases flowing back from later stages of the cycle, expansion through a Joule-Thomson valve and through an air-expansion engine, and fractional distillation for removal of oxygen and further liquefaction.

The air from which the nitrogen is to be separated is first compressed to 3,000 lb/in$^2$ in five stages. Between the second and third compression stages it is run through a tank containing a solution of sodium hydroxide for removal of carbon dioxide. After three more compression stages have brought the pressure to 3,000 lb/in$^2$, the gas flows through a drier containing activated alumina for removal of moisture.

With carbon dioxide and water removed, the gas now consists essentially of nitrogen and oxygen at relatively high pressure. It next enters a heat exchanger which it leaves by two different lines. One line is connected to the cold end of the heat exchanger—about $-145°$ C—the other is connected at a point where the temperature is about 0° C. Through this latter line the high-pressure gas enters an expansion engine. Here its pressure is lowered as it does work against reciprocating pistons. The work thus developed is absorbed by an electric generator, and this loss of energy from the gas results in a lowering of its temperature to about $-140°$ C. Further temperature reduction down to the liquefaction point is then obtained by passage through an auxiliary low-pressure heat exchanger.

The line leaving the cold end of the main heat exchanger goes to an expansion valve, where the pressure is reduced to about 5 atmospheres. The temperature

[2] *A liquid level indicator for condensed gases at low temperatures,* by William E. Williams, Jr., and Emanuel Maxwell, Rev. Sci. Inst. (in press).

**Large reciprocating vacuum pumps in the hydrogen liquefaction plant. These pumps are used to reduce the boiling pressure—and hence the temperature—within the liquid-nitrogen precooler. Dean B. Berky is opening the vacuum beaker on the first of the three vacuum pumps.**

is correspondingly reduced to the liquefaction point by the Joule-Thomson cooling effect, causing a fraction of the air to liquefy.

The expansion engine furnishes a sizable amount of refrigeration which indirectly serves to precool the air going to the expansion valve, thereby increasing by several times the efficiency of the process. Optimum performance of the system is obtained by regulation of the amount of air taken by the expansion engine. This is controlled by the speed of the expansion engine and the time the intake valve is open.

The two streams of partially liquefied nitrogen-oxygen mixture join and flow to a distillation column, where the liquid nitrogen is separated from the mixture. Refrigeration for condensation of the nitrogen vapor that accumulates in the top of the distillation column is obtained by piping some of the oxygen-rich liquid in the bottom of the column into a jacket surrounding the top of the column. The liquid nitrogen is continuously tapped off into a reservoir and periodically transferred to the large storage tanks.

## Safety Devices

Among the many automatic safety devices in the new laboratory is a hydrogen-gas indicator, which continuously samples the air at eight points throughout the plant building. Whenever the hydrogen concentration reaches 10 percent of the lower explosive limit, this device sounds an alarm and automatically closes off all sources of hydrogen. In addition, a ventilating system has been installed that normally changes the air in the building every 2 minutes and is automatically speeded up to effect a complete change once a minute when the hydrogen alarm sounds. Other safety precautions include conducting floors to eliminate static sparks, a system that measures the concentration of oxygen in the hydrogen with a sensitivity of 2 parts in a million, and means for venting hydrogen to the outdoors in an emergency.

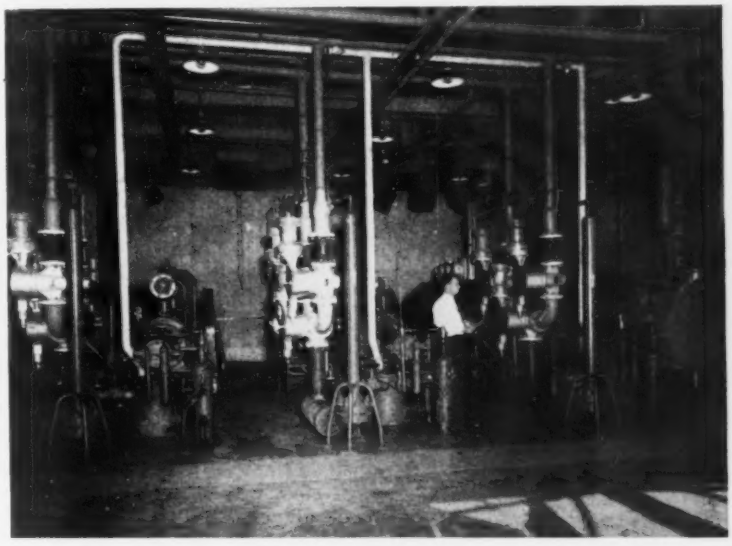
## Research and Development

Research and development at the NBS-AEC Cryogenic Engineering Laboratory are directed principally toward safer and more convenient means for handling liquid hydrogen and toward increased knowledge of the properties of materials at very low temperatures. Efficient design of low-temperature equipment requires information on the mechanical and heat-conducting properties of many metals, alloys, and plastics over a temperature range extending from room temperatures down almost to absolute zero. The Bureau is now developing apparatus for low-temperature measurement of the tensile and impact behavior and fatigue properties of these materials. Such data are at present very meager and are mainly confined to those materials and temperatures encountered in aircraft design. As a first step toward the accumulation of thermal conductivity data, apparatus has been designed which provides results in the temperature range from 2° to 300° K. The new appartus is expected to make possible more rapid collection of data without loss of accuracy.

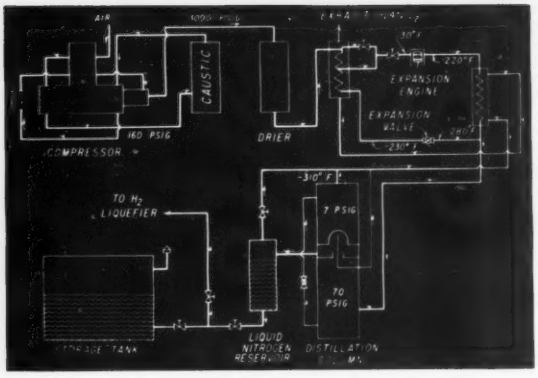
Design of a large-capacity cryostat is also under way. This equipment will be used to provide a controlled low-temperature environment for many different kinds of tests of low-temperature materials.

The Bureau is also working on the design of more efficient insulated lines for transfer or liquefied gases. A major part of this project is the development of valves, fittings, and couplings that will permit easy assembly, extension, and control of flow.

Recently the efforts of the Bureau to obtain liquid parahydrogen on a large scale have met with signal



**Three hydrogen compressors in the liquid hydrogen plant. The compressors are four-stage and are water-cooled. Victor J. Johnson, project leader for plant operations, is standing in front of a bank of air-operated selector valves that connect the compressors to either of the two hydrogen liquefying systems.**




**Flow diagram of the nitrogen liquefier.**

success. Liquid hydrogen as usually produced has a high concentration of the molecular form known as orthohydrogen, in which the diatomic molecules have the two nuclear spins oriented in the same direction. But the low-temperature equilibrium form of hydrogen is nearly pure parahydrogen, in which the nuclear spins in each molecule are opposed. Thus, ordinary liquid hydrogen slowly changes to the para form with an accompanying evolution of heat, and this heat causes a serious loss of liquid hydrogen by evaporation (about 1 percent per hour for fresh normal liquid hydrogen). One of the liquefiers at the Cryogenic Engineering Laboratory has been equipped with a special catalyzing chamber that results in the production of almost pure liquid parahydrogen. This liquid hydrogen, being free of exothermic ortho-para conversion, has excellent keeping qualities and can be stored with little loss for many days.

# *Dielectric Properties of Pure Substances*

A COMPREHENSIVE program for the critical compilation of the dielectric properties of pure substances is being carried out by the National Bureau of Standards with the cooperation of the National Research Council and the International Union of Chemistry. This work, now under the direction of Dr. A. A. Maryott of the NBS staff, is part of a more general program for the examination and compilation of world-wide physico-chemical data of industrial and scientific importance. The information thus far obtained on dielectrics is already being widely employed in pure and applied research and in engineering design.

In recent years data on the properties of dielectric materials have become increasingly important not only to the designer and manufacturer of electronic equipment but also to the scientist who is studying molecular structure. The development of the high-frequency techniques of radar has opened up new areas of research and has given great impetus to the study of dielectrics. Because the literature on dielectrics is large, rapidly expanding, and widely scattered, there has been an acute need for a critical tabulation of selected dielectric properties.

To date, the Bureau has completed and published two tabulations of dielectric properties. The first table of the series appeared as NBS Circular 514, *Table of Dielectric Constants of Pure Liquids*, by Arthur A. Maryott and Edgar R. Smith. This table contains values of the dielectric constant for approximately 800 substances; it includes sections on standard liquids, inorganic liquids, and organic liquids, as well as a complete list of references. In the compilation of the table, the literature was critically examined to provide "best" values of the dielectric constant; the selected values are placed in one of three categories of accuracy. Whenever feasible, the variation of dielectric constant with temperature is represented by a concise function; in other cases values of dielectric constant are tabulated for a number of selected temperatures. The section on standard liquids recommends as reference liquids 10 substances for which the values of dielectric constant range from 1.2 to 80 and are considered to be accurate to 0.2 percent or better.

More recently a second circular (NBS Circular 537) entitled *Table of Dielectric Constants and Electric Dipole Moments of Substances in the Gaseous State*, has been completed by Arthur A. Maryott and Floyd Buckley. Besides listing the dipole moments of about 350 substances, this publication gives best values for the dielectric constants of important reference gases, such as helium, hydrogen, oxygen, argon, air, nitrogen, and carbon dioxide. These values are based upon a consideration of the more reliable data at radio, microwave, and optical frequencies. As many measurements of dielectric constant are of a relative nature, the values for the reference gases will be particularly applicable to the calibration of equipment. A majority of the values of the dipole moment are derived from measurements of dielectric constant, and sufficient information is included to permit the calculation of dielectric constants from these values. Dipole moments determined by molecular-beam and microwave techniques are also listed.

Both NBS Circular 514 (30 cents) and NBS Circular 537 (20 cents) are available from the Superintendent of Documents, U. S. Government Printing Office, Washington 25, D. C.

# ADAPTABLE ELECTRONIC CHASSIS

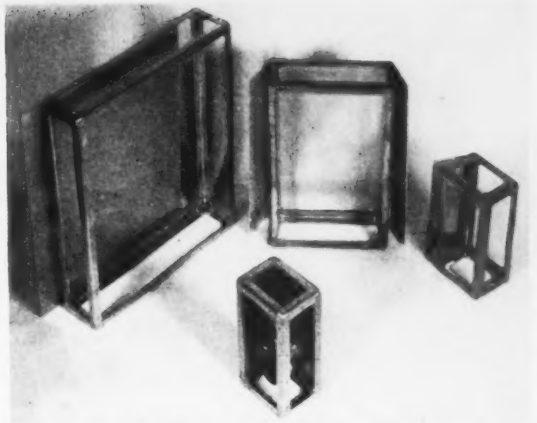
IN RESPONSE to the need for a components chassis that would lend itself to varied and changing electronic design, I. Rotkin and J. Guarracini of NBS have developed a widely adaptable chassis that is both economical and convenient. The design of the new chassis includes a rectangular frame made of $\frac{3}{8}$x$\frac{1}{16}$ in. steel angle and sets of flat plates that are fitted to the frame with screws. The frames vary in size so that chassis may be made up as small 3x4x4 in. boxes, or 3x13x16 in. models, or even whole networks of different-sized chassis.

Conventional electronic chassis, normally built with five sides, often impose restrictions on the movement of tools used to drill and punch the required holes and recesses. After the components have been installed in the chassis and the experimental circuit tested, either a relatively expensive piece of equipment must be thrown away or valuable storage space must be used for an item that is only potentially useful. Even during the development stages of the circuit the design of conventional chassis does not lend itself to exposure of the circuit wiring and tube sockets to facilitate probing and rewiring. Sometimes a great simplification is possible in the construction of equipment if several "breadboard" models can be pieced together, but this is a difficult task requiring complex mechanical structures if the components are mounted in standard chassis.

The chassis developed by NBS are produced in four standard sizes, all 3 in. high; 16x13, 13x8, 8x4, and 4x4 in. Flat cover plates are drilled with holes that match screw-holes in the frames. The dimensions of the chassis and plates were chosen so that the long side of each chassis matches the short side of the next larger size. When desired, any of the six side plates may be left blank or discarded entirely; thus, ventilation may be obtained for circuits requiring air circulation. No restrictions are placed on the kind of material from which the flat plates are made. Consequently, it is possible to eliminate much of the component insulation required when all-metal chassis are used.

In development of a circuit the components may be assembled in "breadboard" style on one or more flat plates before final mounting on a suitable frame. This procedure facilitates and simplifies the often laborious details of drilling, punching, de-burring, or nibbling. Once the units have been mounted in the plates, they may be screwed onto the frames with all the wiring and tube sockets on the open (outer) side of the plate exposed to the probing of the test equipment. If the design and craftsmanship permit, these same plates may later be reversed; the wiring will then be protected, the tubes will be accessible for replacement, and the completed unit is ready for actual operation.

If a component is a prototype or has become obsolete, only the plate containing the circuit in question need be removed from the frame and replaced with the improved circuit. The discarded plate can then be stripped of the easily removable components and stored in a shallow drawer or cabinet until a similarly patterned plate is needed again. If desired, whole clusters of these versatile chassis may be assembled around or on top of a larger chasis—the frames are sufficiently standardized to permit this. In addition, the spacing between the holes permits the mounting of commercially available bakelite terminal strips.



**Several adaptable electronic chassis designed by NBS. The 3x4x4 in. chassis (foreground) illustrates the freedom of accessibility to components in even the smallest model. Other circuits may easily be added by mounting of the components on a plate of the proper size and screwing of the plate to the frame. For special requirements plates of a nonconducting material may be used. The chassis (rear) are, from the left, the 13x16x3, 8x13x3, and 3x4x3 in. models.**

The Richards Company of Arlington, Virginia, which now makes the chassis under contract to the National Bureau of Standards, has contributed several design improvements that have been incorporated in the final model.

## Publications of the National Bureau of Standards

PERIODICALS

Journal of Research of the National Bureau of Standards, volume **51,** number 3, September 1953 (RP2440 to RP2445 incl.). Annual subscription $5.50.

Technical News Bulletin, volume **37,** number 9, September 1953, 10 cents. Annual subscription $1.00.

CRPL–D109. Basic Radio Propagation Predictions for December 1953. Three months in advance. Issued September 1953. 10 cents. Annual subscription $1.00.

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# TECHNICAL NEWS BULLETIN

U. S. DEPARTMENT OF COMMERCE
SINCLAIR WEEKS, *Secretary*
NATIONAL BUREAU OF STANDARDS
A. V. ASTIN, *Director*

**October 1953** **Issued Monthly** **Vol. 37, No. 10**

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### RESEARCH PAPERS

*Reprints from Journal of Research, volume* **51,** *number 3, September 1953. Single copies of Research Papers are not available for sale. The Superintendent of Documents, U. S. Government Printing Office, Washington 25, D. C., will reprint 100 or more copies, and request for the purchase price should be mailed promptly to that office.*

RP2440. Refractive index of cesium bromide for ultraviolet, visible, and infrared wavelengths. William S. Rodney and Robert J. Spindler.

RP2441. An expansion method for parabolic partial differential equations. J. W. Green.

RP2442. Characteristics of internal solitary waves. Garbis H. Keulegan.

RP2443. Becker value of manila rope by photoelectric reflectometry. Sanford B. Newman, Harry K. Hammond III, and Helen F. Riddell.

RP2444. Dielectric relaxation in a styrene-acrylonitrile copolymer during and after its polymerization. Paul Ehrlich and Nicholas J. DeLollis.

RP2445. Study of degradation of polystyrene, using ultraviolet spectrophotometry. Mary Jane Reiney, Max Tryon, and B. G. Achhammer.

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### CIRCULARS

C542. Graphs of the Compton energy-angle relationship and the Klein-Nishina formula from 10 Kev to 500 Mev. Ann T. Nelms. 55 cents.

C543. Reference data for orienting quartz plates by X-ray diffraction. Catherine Barclay and Leland Sogn. 15 cents.

### HANDBOOKS

H44. Correction Sheets. Changes adopted by the Thirty-Eighth National Conference on Weights and Measures, 1953. (To supplement H44, *Specifications, tolerances, and regulations for commercial weighing and measuring devices.* Available upon request from the National Bureau of Standards, Washington 25, D. C.

### PUBLICATIONS IN OTHER JOURNALS

The limiting thickness of an electrolyzed gas film capable of sustaining a given negative pressure. Lyman J. Briggs. J. Chem. Phys. (57 East Fifty-fifth Street, New York 22, N. Y.) **21,** No. 5, 779 (May 1953).

Voltage breakdown tester. W. E. Williams, Jr. Rev. Sci. Instr. (57 East Fifty-fifth Street, New York 22, N. Y.) **24,** No. 6, 458 (June 1953).

Improvement in response of 4-$\pi$ gamma-ionization chambers. C. C. Smith and H. H. Seliger. Rev. Sci. Instr. (57 East Fifty-fifth Street, New York 22, N. Y.) **24,** No. 6, 474 (June 1953).

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The mechanism of formation of OH, CH and HCO in flame spectra, using deuterium as tracer. H. P. Broida and A. G. Gaydon (Imperial College, London). Proc. Royal Society (London) (University Press, Cambridge, England) Series A, **218,** 60 (March 1953).

Measuring the stiffness of paper. R. B. Hobbs and V. Worthington. Modern Packaging (575 Madison Avenue, New York 22, N. Y.) **26,** No. 11, 127 (July 1953).

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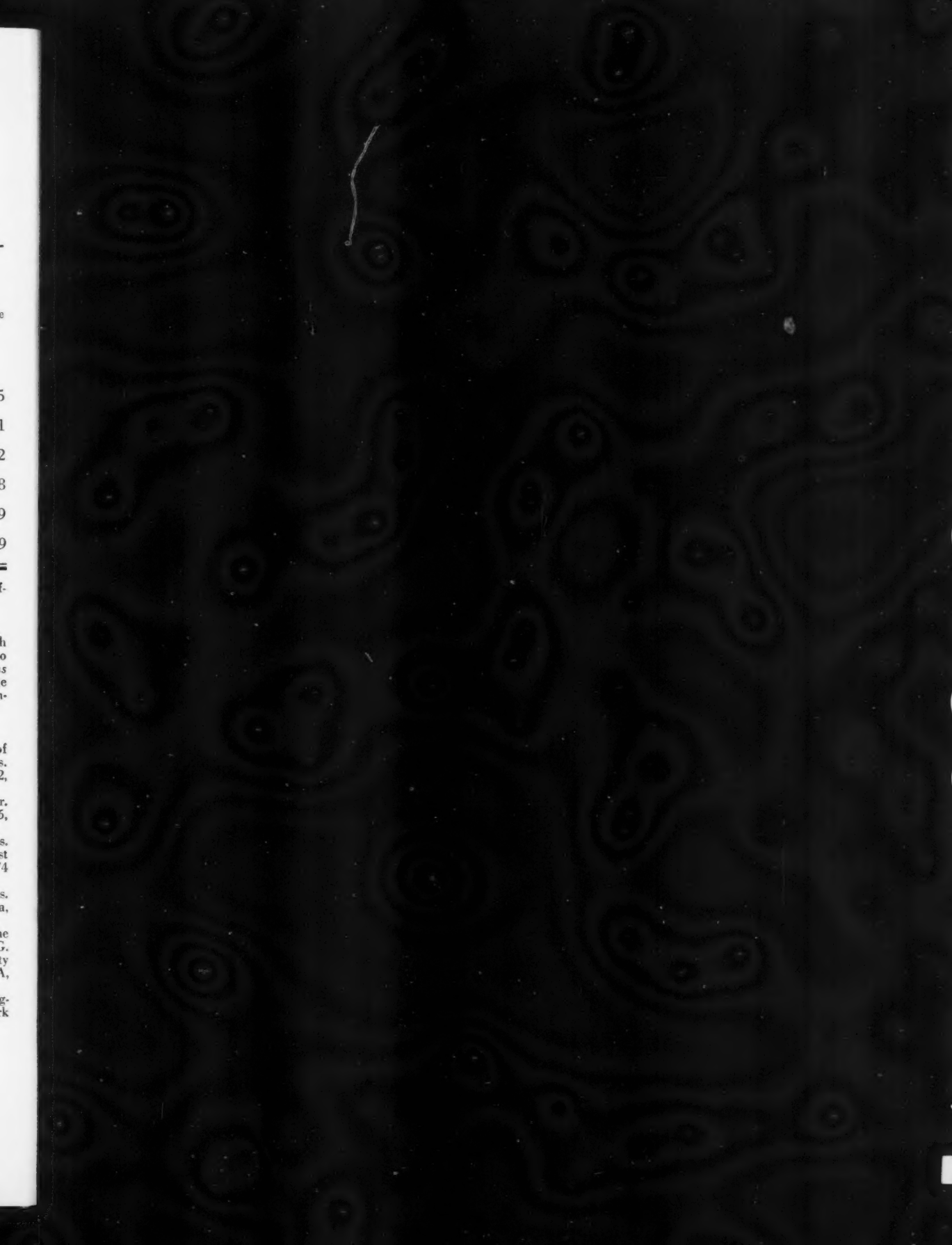
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